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Robert W. Jech
October 1975

Page 12: Replace table II(b) with the attached copy of table II(a), which was omitted. Table II(b) also appears on page 13.

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16. Abstract

Stress-rupture and tensile tests were conducted at 816° C (1500° F) to determine the effect of matrix composition on the minimum fiber length to diameter ratio (critical aspect ratio) below which fibers in a tungsten fiber/copper-nickel alloy matrix composite could not be stressed to their ultimate load carrying capability. This study was intended to simulate some of the conditions that might be encountered with materials combinations used in high-temperature composites. The critical aspect ratio for stress-rupture was found to be greater than for short-time tension, and it increased as the time to rupture increased. The increase was relatively slight, and calculated fiber lengths for long service appear to be well within practical size limits for effective reinforcement and ease of fabrication of potential gas turbine components.

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CRITICAL ASPECT RATIO FOR TUNGSTEN FIBERS IN COPPER-NICKEL MATRIX COMPOSITES

by Robert W. Jech

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SUMMARY

A study was made of the effect of matrix composition on the minimum fiber length to diameter ratio (critical aspect ratio) below which fibers in a metal-fiber/metal-matrix composite cannot be stressed to their ultimate load carrying capability. Tungsten was used as the fiber and copper-nickel alloys were used as the matrix in this model system study. This combination of fiber and matrix was chosen to simulate some of the conditions that might be encountered with materials combinations that might be used in high-temperature composite applications. Single-fiber tensile and stress-rupture pullout tests were conducted at 816° C (1500° F).

It was found that when nickel diffusion from the matrix into the fiber was negligible, the net effect of the alloying element (nickel) was to increase the shear strength of the matrix, which, in turn, resulted in a decrease in the critical aspect ratio. For a stress-rupture life of 100 hours, the critical aspect ratio (L_c/D), as determined by using single fiber pullout specimens, decreased from 26 for specimens having an unalloyed copper matrix to 17 for specimens made with a copper - 10-percent nickel matrix. The critical aspect ratio for stress-rupture life up to 1000 hours was well within the practical size limits for both effective reinforcement and ease of fabrication of potential gas turbine components.

INTRODUCTION

There is a minimum fiber length in a fiber reinforced metal-matrix composite below which the fiber cannot be stressed to its ultimate load carrying capacity and therefore will not provide the most efficient reinforcement (ref. 1). This minmum length is called the critical fiber length l_c and the ratio of the critical fiber length to the fiber diameter D is called the critical aspect ratio l_c/D. The critical length and critical aspect ratio are unique to the particular fiber/matrix combination being used and are functions

of the mechanical properties of the fiber and the matrix, the strength of the bond between them, and the interfiber distance.

When designing a fiber-reinforced composite, it is necessary to know the critical aspect ratio for the fiber/matrix combination under consideration. Some metal and ceramic fibers, which exhibit very high tensile strength or good stress-rupture strength, may only be available in very short lengths. Also, it may be desirable from a fabrication standpoint to use short fibers that are normally produced as long, continuous filaments. In other circumstances, fiber continuity may be interrupted by cutouts or joints which can also result in short fibers in the final composite product.

Previous work (ref. 1) using tungsten as the fiber and unalloyed copper as the matrix, has related the critical aspect ratio in tension to the use temperature of the composite. The results showed that the critical aspect ratio increased with increasing temperature. A second investigation (ref. 2), using the same fiber and matrix, was concerned with the critical aspect ratio for composites where stress-rupture was the failure mechanism. Both of these investigations were concerned with composites in which the matrix and the fiber were mutually insoluble. Although such systems are useful for research, they are not typical of practical composites. In more practical composites, an alloy would generally be used as the matrix to provide properties such as higher strength, oxidation resistance, and toughness. Although there are decided advantages to the use of alloys as the matrix in composites, there may also be disadvantages. Elements such as nickel, cobalt, iron, titanium, and aluminum in a matrix alloy can cause degradation of the fiber (ref. 3).

Reference 4 reported the results of a limited investigation in which the critical aspect ratios of the fibers were determined for composites of tungsten fibers in a copper - 2-percent chromium matrix. It was observed that "alloying the copper matrix increased the matrix shear strength, which was beneficial even though the alloying element reacted with the fiber."

The purpose of the present model system study was to more fully investigate the effect of matrix composition on the critical aspect ratio. The use of copper-nickel alloys as the matrix served to simulate conditions encountered with materials combinations that might be used in high-temperature composite systems. Nickel was used as the alloying element in the copper because it is soluble in both tungsten and copper. It is also the base metal in a great many high-temperature alloys which might be used as matrices for high-temperature composites. In addition, as shown in reference 5, small amounts of nickel, if allowed to diffuse into the tungsten, can have a pronounced effect on the recrystallization, tensile strength, and ductility of the tungsten wire. Copper-nickel alloys with nominal nickel contents of 1, 5, 7.5, and 10 weight percent nickel were used.

Pullout specimens were tested in tension at 816° C (1500° F). Stress-rupture pullout tests were conducted at the same temperature, and the critical aspect ratio was

determined for nominal failure times of 1, 10, 100, and 500 hours. The critical aspect ratios determined by using pullout tests were also compared with approximations of critical aspect ratio made using a simple equation and the known tensile and stress-rupture properties of the constituents. The data obtained earlier (ref. 2) using the tungsten/copper system served as the baseline for comparison with the results for the present study.

MATERIALS, APPARATUS, AND PROCEDURE

Specimen Configuration

Sketches of a single-fiber pullout specimen and a multifiber composite are shown in figure 1. In composites containing discontinuous, uniaxially oriented fibers such as those shown in figure 1(b), the fibers are surrounded by matrix and their long axis is oriented parallel to the long axis or load direction of the specimen. The fibers are bonded to the matrix and separated from each other by the matrix. Ideally, the fiber ends overlap each other (so that there is no more than one fiber end at any cross section), and the fibers are arranged in a hexagonal array. Figure 1(a) is a sketch of a pullout specimen used to simulate the conditions around one fiber in a composite containing about 70 volume percent fibers. In the figure, l refers to the entire fiber length in a composite and L to the embedded length of the fiber in the pullout specimen. The length L of the fiber in the pullout test specimen is equal to one-half the length of a fiber l in an actual multifiber composite. The reason for this is that in a pullout specimen the load is applied to the fiber by gripping and pulling on its free end. In a multifiber composite specimen load is applied to the composite and transferred to the fiber from both ends by shear through the matrix. The diameter of the fiber is represented by D. In the remainder of this report, the aspect ratio L/D used is that of the pullout specimen and must be doubled when referring to an actual multifiber composite. The interfiber distance (IFD) is the distance from one fiber to its neighbors. Another slight difference exists between the pullout specimen and an actual multifiber composite. In a composite containing fibers that are circular in cross section and arranged in a hexagonal array, the IFD varies as shown in figure 1(b) and is not as easily defined as in the pullout specimen. In the pullout speci : en the distance between neighboring fibers present in a multifiber composite is represented by the matrix thickness (fig. 1(a)).

With the button of the single-fiber pullout specimen held in a special fixture, and the load applied to the free end of the fiber, specimen failure occurred by one of two modes: failure of the fiber or failure by pullout, which results from shear failure either in the matrix or at the matrix-fiber interface. Single-fiber pullout specimens with an

aspect ratio less than the critical aspect ratio (L_c/D) fail by pullout (shear). Those having an aspect ratio greater than the critical aspect ratio fail by fracture of the fiber. In other words, the critical aspect ratio is the smallest aspect ratio at which fiber fracture occurs. Figure 2 shows a specimen before testing, a specimen that has failed by fiber fracture ($L/D > L_c/D$), and a specimen that has failed by pullout ($L/D < L_c/D$).

Materials

Fiber. - Type 218CS, unalloyed tungsten wire, in the as-received condition, was used as the fiber in this investigation. The wire was 0.0254 centimeter (0.010 in.) in diameter and was cleaned in boiling hydrogen peroxide followed by a water and alcohol wash before use.

Matrix. - The matrix alloys were prepared in the form of 0.0508-centimeter (0.020-in.) diameter wire. They were made of oxygen-free high-conductivity (OFHC) copper and electrolytic nickel, which had been triple melted in a graphite crucible under an argon atmosphere. Between the first two meltings, the ingots were cold swaged to 0.806-centimeter (0.125-in.) diameter rods, cut up, and remelted. After the third melting, the alloys were cold swaged and cold drawn to their final size. Table I lists the nominal and actual nickel contents of the alloys. In the remainder of this report the alloys will be referred to by their nominal nickel content. Ten percent nickel was the maximum alloy content used because higher nickel content alloys would have had a melting point above the primary recrystallization temperature of the tungsten wire.

Button. - The tungsten buttons were made from cold pressed powder with an average particle size of 5 micrometers. The disks were of various thicknesses and in the cold-pressed condition were about 75 percent full density. A hole, 0.0343 centimeter (0.0135 in.) in diameter, was drilled in the button. After presintering for 2 hours at 1204° C (2200° F) in vacuum to remove the stearic acid binder (used in the cold pressing operation) and sintering for 4 hours at 2204° C (4000° F) in flowing hydrogen, the button was about 91 percent full density. During sintering, the drilled hole diameter shrunk to 0.0317 ± 0.0005 centimeter (0.0125 ± 0.0002 in.). When used with the 0.0254-centimeter (0.010-in.) diameter tungsten wire, the resulting matrix thickness or simulated interfiber distance was 0.0033 centimeter (0.0013 in.).

Specimen Preparation

The tungsten wire, tungsten button, and a helix of either unalloyed copper or copper-nickel alloy were assembled as shown in figure 3. Infiltration was carried out by melting the copper or copper alloy in flowing hydrogen for 15 minutes at 1191° C (2175° F).

The infiltration temperature was slightly higher than that used in previous investigations (refs. 1 and 2) because this was the lowest temperature at which the copper-nickel alloys, which have a slightly higher melting point than unalloyed copper, would infiltrate the specimen. While molten, the copper or copper-nickel alloy not only infiltrated the annulus between the button and the tungsten wire, but also coated the surface of the tungsten wire outside of the button. Subsequent tensile tests of the wire showed no significant difference in tensile strength or ductility of the copper-nickel coated wire from that used in the unalloyed copper matrix specimens of references 1 and 2.

Testing Procedure

Tensile pullout tests. - Tungsten wire/copper and tungsten wire/copper-nickel alloy pullout specimens were tested at 816° C (1500° F). Tests were conducted using a screw-driven constant-crosshead-speed tensile machine. The crosshead speed was 0.127 centimeter per minute (0.050 in./min.). A furnace equipped with a quartz heating lamp was used since this heating source brought the test specimen to the proper temperature in about 1 minute. This, in addition to a protective blanket of flowing helium, helped minimize specimen oxidation. Specimens were held at the test temperature for 5 minutes before the application of the load.

Stress-rupture pullout tests. - The equipment used for the stress-rupture pullout tests was designed so that the long time tests could be conducted in vacuum ($\sim 1.33\times 10^{-1}$ N/m^2 or $\sim 1\times 10^{-3}$ torr) to limit specimen oxidation. Because of the light load involved, conventional stress-rupture equipment was impractical; direct loading was therefore used.

Figure 4 shows a sketch of the apparatus. The pullout specimen was mounted in a heat sink holder, and the weight attached to the free end of the wire. This was enclosed in a chamber which was evacuated using a mechanical pump. The weight was held by the retractable weight pan while the specimen was heated to the test temperature. The specimen was loaded by retracting the weight pan. Failure time was recorded to the nearest 0.01 hour by a timer activated by a microswitch. Specimen temperature was monitored by thermocouples mounted in the specimen holder. During the tests, the specimen temperature was held at $816^{\circ}\pm 3^{\circ}$ C ($1500^{\circ}\pm 5^{\circ}$ F). Temperature variation along the test length of the specimen (i.e., the button and 2.54 cm (1.0 in.) of the wire), was $\pm 1^{\circ}$ C ($\pm 2^{\circ}$ F).

RESULTS AND DISCUSSION

Experimental Determination of Critical Aspect Ratio

Nickel additions to a copper matrix were used to study the effect of matrix composition on the critical aspect ratio in tungsten-fiber-reinforced composites. Typical data from tensile and stress-rupture pullout tests conducted at 816° C (1500° F) are shown in figures 5 and 6. Both figures present results for specimens made with copper - 1 percent nickel matrix. Additional plots were prepared for specimens containing 5, 7.5, and 10 percent nickel in copper, but because of their similarity, they have not been included in this report. Complete data for all the tensile and stress-rupture pullout tests are listed in table II. In figure 5 the results of the tensile tests are plotted according to failure load, aspect ratio, and whether the specimen failed by pullout (shear) or fiber fracture. In figure 6, which is for stress-rupture, the data are plotted according to failure time, aspect ratio, and failure mode. In both types of tests the aspect ratio at the knee of the curve was taken as the critical aspect ratio L_c/D. The horizontal line in figure 5 for the tensile tests represents the average load for fiber failure. For the stress-rupture tests, in (fig. 6), it represents the average time for fiber failure. The inclined line for the tensile tests was drawn from the origin to the data point for the smallest aspect ratio specimen that failed by fiber fracture. For the stress-rupture tests the inclined line was a least squares fit of the pullout (shear) failure data points.

From figure 5, the critical aspect ratio in tension at 816° C (1500° F) for a pullout specimen made with tungsten fiber and a matrix of copper - 1-percent nickel alloy was 10.5. The critical aspect ratio for 10 hours stress-rupture life and for the same type of specimen, increased to 21 (fig. 6). Table III presents a summary of critical aspect ratios determined for all of the tensile and stress-rupture tests conducted at 816° C (1500° F) for all of the alloys. These data are plotted in figure 7. A cross-plot of figure 7 is shown in figure 8, where the critical aspect ratios for tensile and various stress-rupture failure times using various copper-nickel alloys as the matrix are compared.

Figure 8 shows that nickel additions to the matrix changed the critical aspect ratio both in tension and stress-rupture. In tension, at 816° C (1500° F), the critical aspect ratio was 19.8 for pullout specimens made with an unalloyed copper matrix; it decreased to 5.4 for specimens made with a copper - 10-percent nickel alloy matrix. This was achieved with practically no change in the tensile strength of the tungsten fiber. As may be seen in table IV, the average tensile strength of the tungsten fiber from the unalloyed copper matrix pullout specimens was 1060 meganewtons per square meter (154 ksi), and, for the tungsten fiber from the pullout specimens made with the copper - 10-percent nickel matrix, the average tensile strength was 1020 meganewtons per square meter (148 ksi). At the same time, the average shear strength of the copper matrix increased

from 15 meganewtons per square meter (1200 psi) in the unalloyed condition to 64 meganewtons per square meter (9300 psi) for copper containing 10 percent nickel (table V).

Generally, the same trends can be seen in the stress-rupture pullout specimens. For the same stress rupture time, the L_c/D decreased with increasing nickel content in the copper matrix (fig. 8). For a nominal stress-rupture life of 10 hours at 816° C (1500° F), the critical aspect ratio decreased from 23 for pullout specimens made with an unalloyed copper matrix to 12.5 for pullout specimens made with 10 percent nickel in the copper. The decrease in the L_c/D as the nickel content in the copper increased, is directly attributable to the increased shear strength of the copper-nickel alloy matrix. Table VI lists the shear stress necessary for failure of the copper and copper-nickel alloys in 1, 10, and 100 hours at 816° C (1500° F). The apparent shear strength of the matrix was calculated using the failure load on the specimen and the dimensions of the specimen at the tungsten fiber - copper alloy matrix interface. As the nickel content of the alloys increased, the stress for failure increased as well. Just as in the case of the tensile pullout specimens, the strength of the tungsten fiber did not change significantly (table VII).

In this investigation the strength of the tungsten fiber was about the same for all the tensile pullout specimens (table IV) regardless of the copper-nickel alloy used as the matrix. The stress necessary for fiber failure in a particular stress-rupture time was also constant regardless of the copper-nickel alloy used as the matrix (table VII). The only variable was the strength of the copper-nickel matrix alloys (tables V and VI). As the strength of the matrix alloys increased, the critical aspect ratio decreased. Small increases in the nickel content of the matrix had a marked effect on its strength, and this, in turn, had a marked effect on the critical aspect ratio. It is important to realize, however, that the exact L_c/D values shown are unique to the materials system under study. Other systems should behave in similar fashion, but the numerical values of the L_c/D will differ depending on the tensile strength of the fiber used and the shear strength of the matrix.

The conditions represented by the pullout tests made with unalloyed copper as the matrix are representative of metal-fiber/metal-matrix systems where the fiber and the matrix are insoluble. The tests made with tungsten fibers in copper-nickel alloy matrices are representative of the case where one alloying element can diffuse from the matrix into the fiber. Thus nickel is soluble in both copper and tungsten, and the diffusion of nickel from the matrix to the fiber can occur. However, the relatively short fabrication time at temperature (15 min at 1191° C (1500° F)) prevented any measurable diffusion of the nickel from the alloy matrix into the tungsten fiber.

The relatively small change in the critical aspect ratio when comparing tensile test results with stress-rupture test results for lives up to 1000 hours is also apparent from figure 8. The critical aspect ratio for pullout specimens made with 10 percent nickel

in the copper matrix increased from 5 for short time tensile tests at 816° C (1500° F), to 20 for 1000 hours of stress-rupture life at the same temperature. These results indicate that very long fibers are not necessary even when such a weak high-temperature alloy as copper - 10-percent nickel is used as the matrix. If a 0.0254-centimeter (0.010-in.) diameter tungsten fiber were used, the critical fiber length L_c in a pullout specimen would be 0.508 centimeter (0.200 in.), based on the 1000-hour stress-rupture results. Since the critical fiber length L_c in a pullout specimen is one-half the critical fiber length in an actual multifiber composite l_c, the critical length in the multifiber composite would be only 1.016 centimeter (0.400 in.).

Calculation of the Critical Aspect Ratio

When diffusion between the matrix and the fiber is negligible, the critical aspect ratio for a single-fiber pullout specimen L_c/D tested in tension or stress-rupture can be approximated by the equation

$$\left(\frac{L_c}{D}\right)_t = \left(\frac{\sigma}{4\tau}\right)_t$$

where

L_c critical fiber length

D fiber diameter

t failure time

σ fiber tensile stress for failure in time t

τ matrix shear stress for failure in time t

This equation is a modified version of equation (1) in reference 1.

The applicability of this equation was checked by using it to calculate the critical aspect ratios required for short time composite use (tension) and long time use (stress-rupture) at 816° C (1500° F), for the tungsten fiber/copper - 10-percent nickel alloy matrix system. These were compared with the results of the single-fiber pullout tests conducted in this investigation. Tungsten fiber tensile and stress-rupture strengths σ used in the calculations are listed in tables IV and VII and were experimentally determined. The shear strengths τ of the copper - 10-percent nickel matrix alloy used in the calculations are listed in tables V(b) and VI(b) for tensile and stress-rupture conditions. The shear strength of the matrix alloy was determined by assuming that the shear strength was equal to one-half the experimentally determined tensile strength as reported in reference 4.

For pullout specimens under short time tensile conditions, the calculated L_c/D was 10.6, while the experimentally determined value was 5.4. For 1, 10, and 100 hours of stress-rupture life, the calculated critical aspect ratios were, respectively, 16.0, 19.1, and 22.0. The values experimentally determined, using pullout specimens, were 8.5, 12.5, and 16.0, respectively. The calculated values of L_c/D were within a factor of 2 of the experimental values. Although the equation results in L_c/D values different from experimentally obtained values, the calculated approximations are all greater. The equation may be considered satisfactory for design purposes in that it provides conservative estimates.

It should be noted that for applications of metal-matrix composites to such aerospace components as compressor and turbine blades, the critical fiber lengths established in this study are reasonable from a handling and fabrication standpoint.

CONCLUDING REMARKS

The results of this composite model system investigation show that, for tensile and stress-rupture applications, the critical aspect ratio for single-fiber pullout specimens is dependent on the shear strength of the matrix and the tensile strength of the fiber when no measurable diffusion of matrix alloying elements into the fiber occurs. When alloying increases the shear strength of the matrix, the critical aspect ratio decreases. The condition of negligible diffusion from the matrix alloy into the fiber is desirable and is sought in practical metal-fiber/metal-matrix composite applications because diffusion from the matrix to the fiber can cause a decrease in the fiber strength. Such behavior has been observed in composites of tungsten fiber in nickel base alloys (ref. 3) as well as in composites of boron fiber in titanium alloys.

SUMMARY OF RESULTS

A study was made of the effect of matrix composition on the critical aspect ratio in model system tungsten - fiber-reinforced copper-nickel alloy matrix composites. Single-fiber pullout specimens were used to simulate multifiber composites. Copper containing 1, 5, 7.5, and 10 weight percent nickel were used as the matrices. The single-fiber pullout specimens were tested in tension and stress-rupture 816° C (1500° F). The major results and conclusions of the investigation are

1. The critical aspect ratio of reinforcing fibers in a multifiber composite, as determined by single-fiber pullout tests, is greater for stress-rupture applications than for tensile applications. However, the difference is comparatively small. For example, at 816° C (1500° F) the critical aspect ratio for single-fiber pullout specimen composed of a tungsten fiber in a copper - 10-percent nickel matrix was 5.4 in tension and 12.5

for 100 hours stress-rupture life.

2. The critical aspect ratio in stress-rupture increased as the stress-rupture life increased (decreasing applied stress). For example, in the case of a tungsten fiber/copper - 1-percent nickel matrix composite tested at 816° C (1500° F), the critical aspect ratio for 10 hours stress-rupture life was 18.5 and 24.0 for 100 hours life.

3. As the shear strength of the matrix was increased, in this case by increasing the nickel content in the copper-nickel matrix alloys, the critical aspect ratio became smaller. This was true for both tensile and stress-rupture conditions. As an illustration of this effect, the critical aspect ratio for 10 hours stress-rupture life at 816° C (1500° F) for the tungsten/copper - 1-percent nickel matrix composite was 18.5. This decreased to 12.5 when the copper matrix contained 10 percent nickel.

4. An approximation of the critical aspect ratio for single-fiber pullout specimens can be calculated from the known mechanical properties of the constituents by the equation

$$\left(\frac{L_c}{D}\right)_t = \left(\frac{\sigma}{4\tau}\right)_t$$

where L_c is the fiber length, D is the fiber diameter, the subscript t is the failure time, σ is the fiber tensile stress for failure in time t, and τ is the matrix shear stress for failure in time t. The equation is applicable for either tensile or stress-rupture conditions where negligible diffusion of the matrix alloying element into the fiber has taken place.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 8, 1975,
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TABLE I. - CHEMICAL ANALYSIS OF COPPER-NICKEL ALLOYS

Nickel content, wt.%	
Nominal	Actual
1	0.77
5	4.62
7.5	7.15
10	10.65

TABLE II. - RESULTS OF PULLOUT TESTS ON TUNGSTEN FIBER/COPPER AND TUNGSTEN FIBER/COPPER-NICKEL ALLOY SPECIMENS

[Test temperature, 816° C (1500° F).]

(a) Tensile tests

Alloy, wt.% nickel	Aspect ratio	Failure mode	Failure load	
			N	lbf
1	6.1	Pullout[a]	38.96	8.76
	7.7	↓	40.21	9.04
	8.7	↓	50.44	11.34
	9.5	↓	47.68	10.72
	9.6	↓	52.66	11.84
	10.5	Fiber	54.53	12.26
	11.5	↓	56.58	12.72
	14.3	↓	52.22	11.74
	16.1	↓	52.84	11.88
	18.0	↓	54.80	12.32
	20.0	↓	54.53	12.26
	22.6	↓	53.73	12.08
	27.4	↓	52.58	11.82
5	5.0	Pullout	42.97	9.66
	6.3	Pullout	49.28	11.08
	7.4	Fiber	52.75	11.86
	8.6	↓	54.35	12.22
	9.5	↓	55.07	12.38
	9.8	↓	52.75	11.86
	10.6	↓	55.24	12.42
	11.4	↓	53.46	12.02
	14.3	↓	53.46	12.02
	16.2	↓	50.89	11.44
	18.0	↓	54.00	12.14
	20.0	↓	54.62	12.28
	22.0	↓	53.38	12.00
	22.0	↓	52.93	11.90
	29.7	↓	51.51	11.58
7.5	4.2	Pullout	46.53	10.46
	5.0	Pullout	51.69	11.62
	6.3	Fiber	53.38	12.00
	7.3	↓	51.77	11.64
	8.1	↓	54.53	12.26
	10.1	↓	53.38	12.00
	14.9	↓	54.98	12.36
10	3.2	Pullout	46.17	10.38
	4.5	Pullout	52.31	11.76
	5.4	Fiber	50.71	11.40
	6.2	↓	51.06	11.48
	14.9	↓	51.69	11.62

[a]Shear.

TABLE II. - Concluded.

(b) Stress-rupture tests

Alloy, wt % nickel	Wire stress, MN/m²	Wire stress, ksi	Aspect ratio	Failure mode	Failure time, hr
0	720	104	23.2	Pullout	41.55
			25.7	Pullout	204.13
			26.0	Fiber	303.99
			29.5		217.12
			30.1		294.18
			32.0		287.20
			35.0		296.21
			40.0		285.05
1	966	140	10.7	Pullout	0.03
			14.6		.36
			15.0		.50
			16.0		.81
			17.0	Fiber	.96
			18.2		1.83
			18.4		1.75
			18.6		.88
			19.9		.94
			20.3		.69
			25.5		1.17
			29.7		1.39
			33.6		.81
	905	131	14.2	Pullout	1.04
			18.7	Pullout	4.70
			20.8	Fiber	11.66
			25.7		12.90
			27.8		4.60
			27.9		4.66
			29.7		5.82
			35.1		14.47
			48.2		22.20
	826	120	13.6	Pullout	0.51
			16.7		2.46
			19.4		11.57
			21.7		33.36
			22.0		51.34
			23.5	Fiber	47.35
			27.1		30.30
			27.8		32.58
			29.9		40.22
			34.9		74.09
			48.2		46.70
	720	104	9.8	Pullout	0.05
			14.7		6.23
			17.6		16.60
			22.9		178.36
			25.4	Fiber	230.25
			26.7		229.37
			29.2		165.49
			29.6		364.36
			30.0		225.98
			35.0		257.88
			40.0		211.10
5	966	140	9.5	Pullout	0.18
			14.3	Pullout	.36
			19.0	Fiber	.67
			20.0		1.82
			24.0		1.23
			26.8		1.96
			35.0		.82
			40.0		.91
	905	131	19.0	Pullout	1.20
			20.0	Fiber	8.45
			21.0		11.26
			22.0		11.79
			24.0		8.53
5	[illegible]	131	27.0	Fiber	5.84
			29.3		8.90
			29.4		5.60
			35.0		17.44
			40.0		16.03
	826	120	17.3	Pullout	1.62
			18.0	Fiber	63.56
			19.0		92.35
			20.0		99.02
			22.1		29.22
			29.4		59.26
			35.0		88.31
			40.0		62.20
	720	104	19.0	Pullout	4.92
			20.0	Pullout	179.34
			22.0	Fiber	386.51
			24.3		276.19
			26.0		269.97
			29.4		306.39
			35.0		201.85
			40.0		297.60
7.5	905	131	10.0	Pullout	0.94
			11.0		1.50
			12.2		4.33
			14.0		8.41
			15.0	Fiber	14.79
			15.0		4.76
			17.0		3.85
			19.0		3.90
			19.0		24.64
			20.0		34.19
			20.1		4.07
			21.0		7.02
			21.0		34.30
			30.0		6.44
			30.0		27.04
	720	104	11.0	Pullout	19.18
			13.0		13.29
			15.0		43.11
			16.0		28.81
			17.0		179.74
			18.0	Fiber	339.97
			20.0		501.10
			21.0		269.34
			29.0		259.38
			30.0		181.63
10	905	131	10.0	Pullout	2.36
			11.2	Pullout	3.89
			13.0	Fiber	8.20
			15.0		10.16
			17.0		11.85
			18.0		14.84
			23.0		15.97
			30.0		6.75
	720	104	13.0	Pullout	52.71
			14.0		68.60
			16.0		97.31
			17.0		135.27
			17.0		140.23
			18.0	Fiber	133.52
			19.0		289.05
			21.0		184.42
			22.0		141.62
			29.7		166.10
			30.0		222.42

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TABLE III. - CRITICAL ASPECT RATIOS OF TUNGSTEN FIBER/COPPER AND TUNGSTEN FIBER/COPPER-NICKEL ALLOY PULLOUT SPECIMENS

[Tested in tension and stress-rupture at 816° C (1500° F).]

Alloy, wt % nickel	Test	Average rupture time for wire failure, hr	Critical aspect ratio
0	Tensile	------	[a]19.8
	Stress rupture	1.37	[a]20.0
	↓	10.33	[a]23.0
	↓	42.31	[a]27.5
	↓	280.62	26.0
1	Tensile	------	10.5
	Stress rupture	1.16	17.0
	↓	12.44	21.0
	↓	44.77	22.0
	↓	240.63	25.4
5	Tensile	------	7.4
	Stress rupture	1.24	19.0
	↓	10.43	20.0
	↓	73.41	13.0
	↓	289.75	22.0
7.5	Tensile	------	6.3
	Stress rupture	14.09	15.0
	Stress rupture	310.20	18.0
10	Tensile	------	5.4
	Stress rupture	11.29	13.0
	Stress rupture	193.69	18.0

[a]From ref. 2.

TABLE IV. - TENSILE STRENGTH

OF TUNGSTEN FIBER

[Test temperature, 816° C (1500° F); obtained from pullout specimens made with various copper-nickel matrix alloys.]

Alloy, wt % nickel	Average tensile strength	
	MN/m^2	ksi
[a]0	[a]1060	[a]154
1	1070	155
5	1050	152
7.5	1060	154
10	1020	148

[a]From ref. 2.

TABLE V. - SHEAR STRENGTH OF COPPER

AND COPPER-NICKEL

[Test temperature, 816° C (1500° F).]

(a) Calculated from tensile pullout tests

Alloy, wt % nickel	Shear strength	
	MN/m^2	psi
[a]0	[a]15	[a]2100
1	28	4000
5	40	5900
7.5	54	7800
10	64	9300

(b) Calculated from tensile tests of alloy (shear strength = 0.5 tensile strength)

Alloy, wt % nickel	Tensile strength		Shear strength	
	MN/m^2	psi	MN/m^2	psi
10	48	7000	24	3500

[a]From ref. 2.

TABLE VI. - SHEAR STRESS ON COPPER AND COPPER-NICKEL ALLOYS TO CAUSE FAILURE IN 1, 10, AND 100 HOURS

[Test temperature, 816° C (1500° F).]

(a) Calculated from stress-rupture pullout tests

Alloy, wt % nickel	Time to failure, hr					
	1		10		100	
	Shear stress					
	MN/m^2	psi	MN/m^2	psi	MN/m^2	psi
[a]0	[a]13	[a]1900	[a]10	[a]1500	[a]8	[a]1100
1	14	2000	11	1600	8	1200
5	13	1800	11	1600	10	1400
7.5	22	3200	17	2400	11	1600
10	24	3500	18	2600	12	1700

(b) Calculated from stress-rupture tests of alloy (shear stress = 0.5 tensile stress)

Alloy, wt % nickel	Time to failure, hr											
	1		10		100		1		10		100	
	Shear stress											
	MN/m^2	psi	MN/m^2	psi	MN/m^2	psi	MN/m^2	psi	MN/m^2	psi	MN/m^2	psi
10	33	4850	24	3500	17	2500	17	2425	12	1750	9	1250

[a]From ref. 2.

TABLE VII. - TENSILE STRESS ON TUNGSTEN FIBER

TO CAUSE RUPTURE IN 1, 10, AND 100 HOURS

[Test temperature, 816° C (1500° F); obtained from pullout specimens made with various copper-nickel matrix alloys.]

Alloy, wt % nickel	Time to failure, hr					
	1		10		100	
	Tensile stress					
	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi
[a]0	[a]1010	[a]146	[a]890	[a]129	[a]780	[a]113
1	1010	146	890	129	770	112
5	990	144	890	129	770	112
7.5	1070	155	930	135	790	115
10	1070	155	920	133	770	112

[a]From ref. 2.

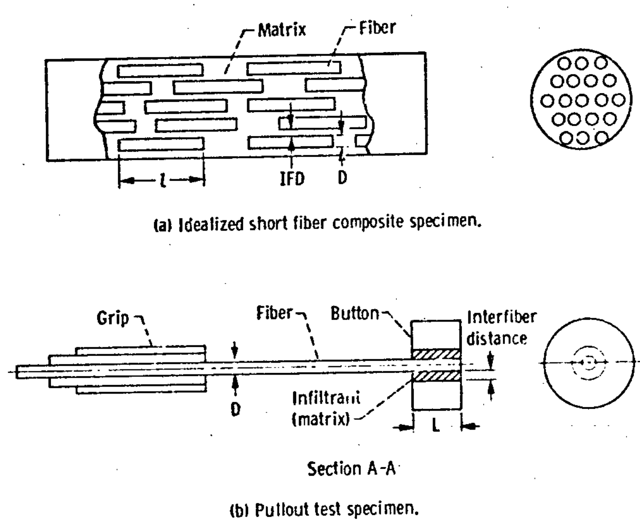

Figure 1. - Pullout test specimen and short fiber composite specimen.

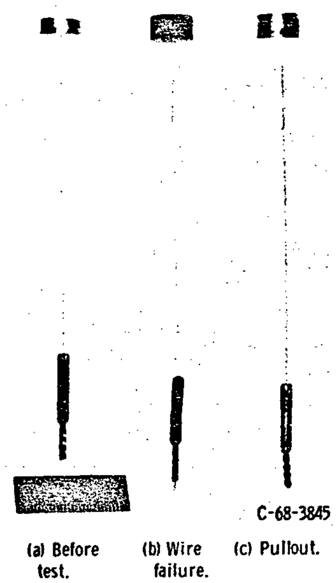

Figure 2. - Single-fiber pullout specimens.

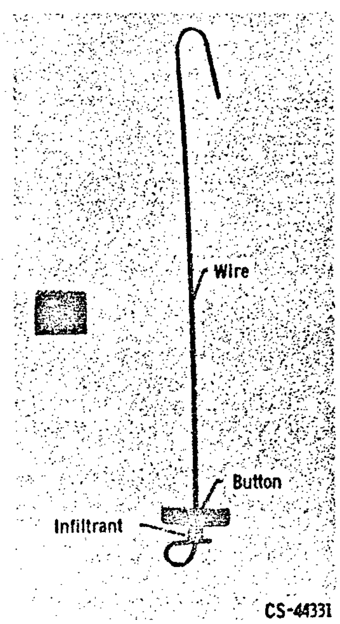

Figure 3. - Pullout specimen before infiltration.

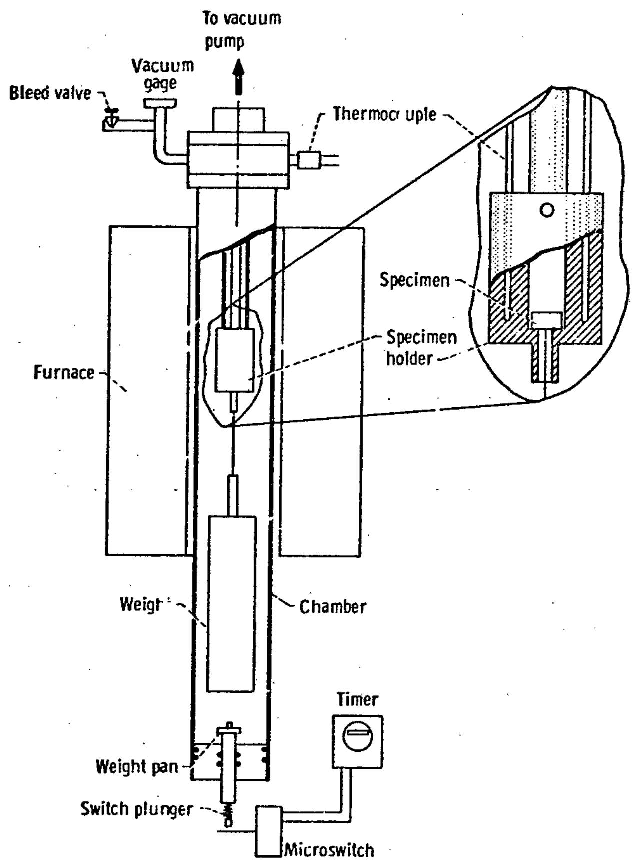

Figure 4. - Layout of vacuum stress-rupture test equipment (inset) detail of specimen and specimen holder.

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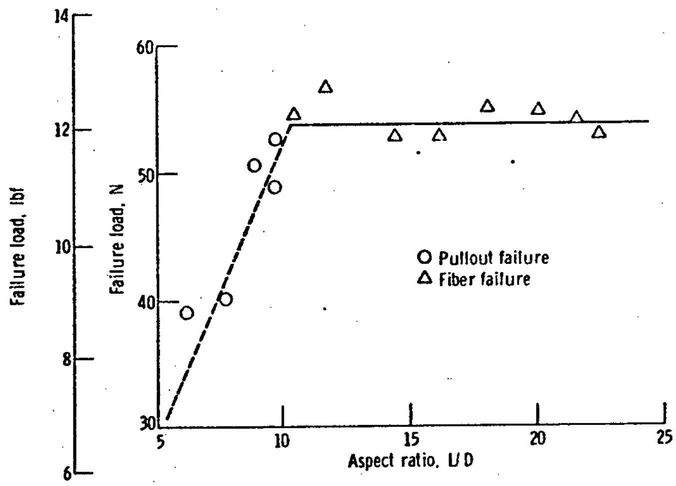

Figure 5. - Failure load and mode at various aspect ratios for tungsten fiber/ copper - 1-percent nickel alloy tested in tension at 816° C (1500° F).

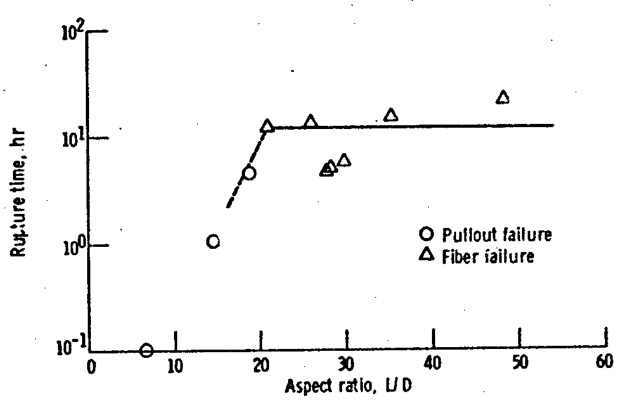

Figure 6. - Failure time and mode at various aspect ratios of tungsten fiber/ copper - 1-percent nickel alloy tested in stress-rupture at 816° C (1500° F). Fiber stress, 905 meganewtons per square meter (131 ksi).

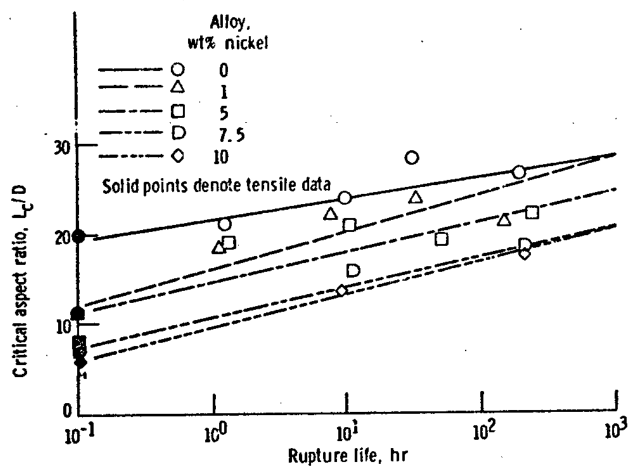

Figure 7. - Critical aspect ratio in stress-rupture for tungsten fiber/ copper and tungsten fiber/ copper-nickel alloy pullout specimens tested at 816° C (1500° F).

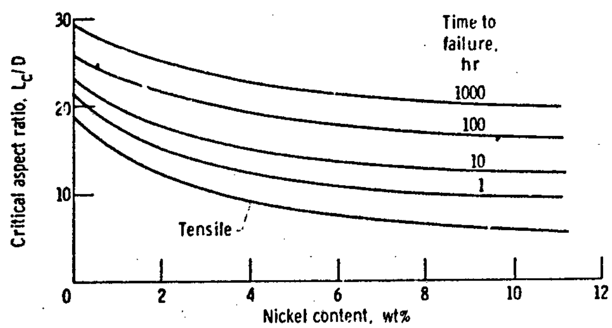

Figure 8. - Critical aspect ratio in tension and stress-rupture for tungsten fiber/ copper and tungsten fiber/ copper-nickel alloy pullout specimens tested at 816° C (1500° F).